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THE INFLUENCE OF RAINFALL ON TRANSPORT OF BEACH SAND BY WIND

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ABSTRACT

This paper deals with the effect of rainfall on the process of wind erosion of beach sands and presents results from both field and wind tunnel experiments. Although sediment transport by splash is of secondary importance on coastal dunes, splash–saltation processes can move sediments in conditions where no motion is predicted by aeolian processes. The effect of raindrop impact on the movement of soil particles by wind was measured on a sand beach plain using an acoustic sediment sampler. In general, an increase of particle movement by wind at the sensor heights was observed during rainfall. Rainfall also affected the wind erosion process during and after rain by changing the cohesive conditions of the surface. The influence of the surface moisture content on the initiation of wind erosion and on the vertical distribution of transported sand particles was studied in a wind tunnel. Moisture significantly increased threshold wind velocities for the initiation of sediment transport and modified vertical sediment profiles.

KEY WORDS aeolian sand transport; beach; rainfall; surface moisture; wind tunnel

INTRODUCTION

The movement of sand by wind results from momentum transfer from the air to sand particles. The effect of rainfall on the ability of wind to cause movement and abrasion of soil is complex and confounded by many variables. Rainfall may initiate splash–saltation, a process in which particles are lifted by raindrop impact and subsequently transported by the wind. Jungerius *et al.* (1981), as well as De Ploey (1980), recorded appreciable wind erosion on dunes during rainy days, and assumed it was due to the combined action of upward movement of splashed sand followed by wind drag (Jungerius and Dekker, 1990). Aina *et al.* (1977) noticed that highly erosive rains are generally those in which peak rainfall intensity and peak wind velocity coincide.

The moisture content at the soil–air interface, resulting from rainfall, greatly influences the susceptibility of the soil to wind erosion (Figure 1). Moisture increases the resistance of the soil particles against lift and drag, due to cohesive forces of the adsorbed water films surrounding them (Chepil, 1958). The effect of moisture on wind erosion processes has been treated by, among others, Belly (1964), Bisal and Hsieh (1966), Svasek and Terwindt (1974), Azizov (1977), Hotta *et al.* (1984), Sarre (1988) and McKenna-Neuman and Nickling (1989). Most of these studies focus on the influence of surface moisture on the threshold velocity, rather than on sediment transport rates. The wind tunnel experiments of Belly (1964), Bisal and Hsieh (1966) and Azizov (1977) proved that the threshold wind friction velocity (u_{*t}) significantly increases with the surface moisture content. Svasek and Terwindt (1974) compared their field measurements on a beach, with sand having a median grain size of 250 μm, with the findings of Belly, who used much coarser sand

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Figure 1. Moist sand is not easily transported by wind. The forms (about 0·1 m in height) are due to differences in the cohesive forces of the adsorbed moisture in the upper sand layers (island of Schiermonnikoog, The Netherlands)

($d_{50} = 400\,\mu$m). They found that the critical friction velocity increased more strongly with moisture content at the surface, and stated that grain size was a determining parameter in the relationship between u_{*t} and the moisture content. McKenna-Neuman and Nickling (1989) showed that particle size determines the moisture tension (and thus capillary forces) at a certain gravimetric moisture content. Therefore, moisture tension is a more appropriate parameter to represent the resistance of the sand to entrainment. Differences in empirical relations between u_{*t} and moisture content, reported by various investigators, are likely to be the result of differences in textural characteristics of the tested sediments. The study of Sarre (1988), on a beach with sand having a mean grain size of $170\,\mu$m, deals with the effect of surface moisture on sediment transport rates. Sarre, surprisingly, found that sediment transport rates are hardly affected by moisture up to a moisture level of 14 per cent. Above this level, sediment transport gradually ceases.

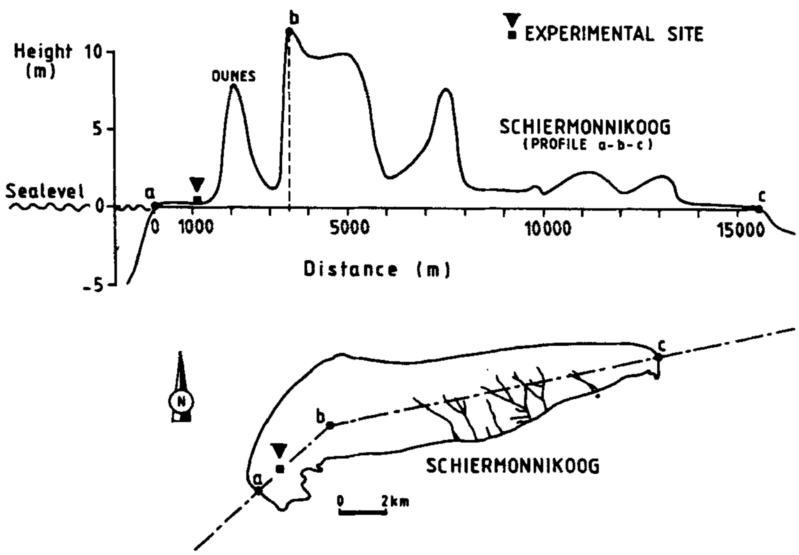


Figure 2. Location of the experiment site on the coastal sand plain on Schiermonnikoog Island, in the north of the Netherlands

Table I. Grain size distribution of the beach sand (as percentage of sand in grain size classes); samples were collected at a depth of 0–30 mm (after Lima *et al.*, 1992)

<63 μm	63–125 μm	125–180 μm	180–250 μm	250–500 μm	>500 μm
0	3·3	51·8	43·5	1·4	0

Summarising, knowledge of the role of precipitation in wind erosion studies is important for two major reasons: (a) intensive wind-driven rain can transport sediments by combined splash and saltation processes; (b) residual moisture increases the cohesive forces between particles and therewith the resistance of the soil against lift by wind drag.

In this paper the effects of rainfall on wind erosion of a beach sand are investigated. The objective is to quantify the effects in order to evaluate their relative importance. Results from field and wind tunnel experiments are presented. The study was carried out using fine, well sorted beach sand of one particular beach. Therefore, the effects of grain size are not discussed here, although the effects of rainfall on wind erosion will be different when other sediments are considered.

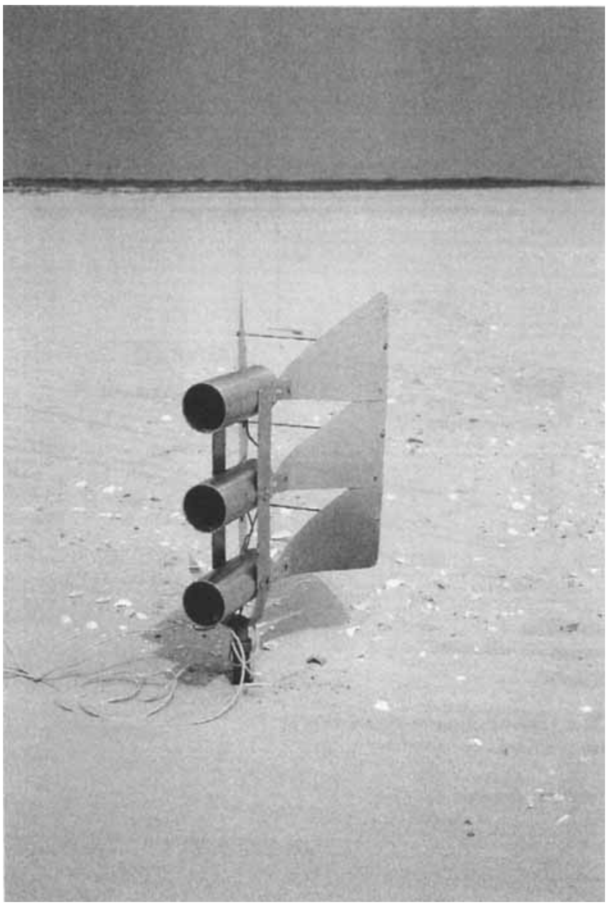


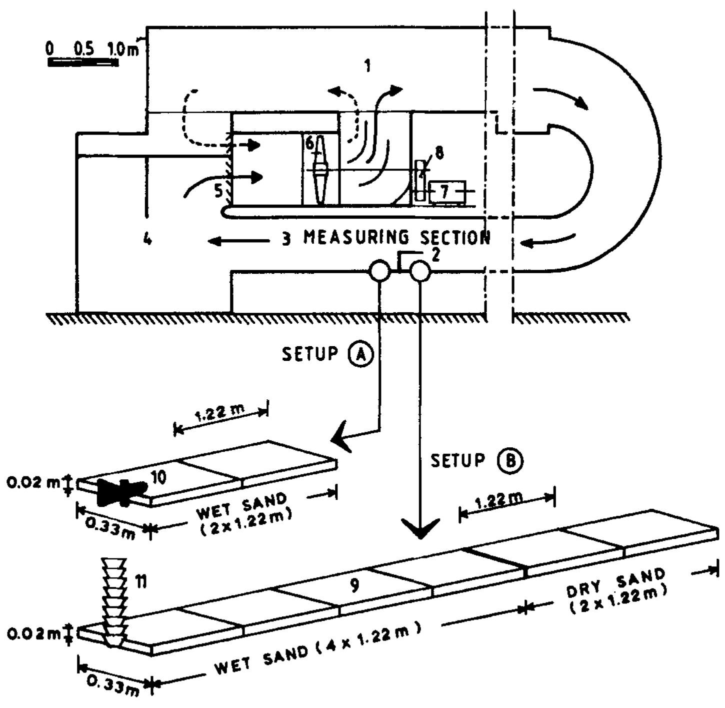
Figure 3. The three saltiphones (Spaan *et al.*, 1991; Lima *et al.*, 1992) installed on the flat coastal plain of Schiermonnikoog Island

RESEARCH SITE AND INSTRUMENTS

Field experiments were conducted on the island of Schiermonnikoog in The Netherlands (Figure 2). Schiermonnikoog is the most northeastern island of the Dutch Waddensea district. The experiments were conducted in autumn 1989 and spring 1990. More than 90 per cent of the beach sand particles are between 125 and 250 μm ($d_{50} = 170\,\mu$m), and these are easily transported by wind (Table I).

For the field experiments the following equipment and instruments were used:

- anemometers at 1, 2 and 10 m above the sand surface;
- relative air humidity meter at 2 m height;
- thermocouples for temperature measurements at 0·1 and 5 m;
- wind vane at 10 m;
- rain-gauge with inlet at 1 m height;
- sediment sensors, called saltiphones, at 0·1, 0·2 and 0·3 m, for measuring particle transport by wind (Figure 3). The sampler detects air-borne particles larger than 50 μm through an acoustic (microphone)



Legend
→ Direction of air current in main circuit
- → Direction of air current in bypass
1 Loft (return flow and partly bypass)
2 Pitot tube at 0·3 m height
3 Observation section. Length: 20 m, cross section: 0·75 m × 0·75 m
4 Sand settling box (2·2 m × 1·5 m × 2·5 m)
5 Blinds for precision control
6 Fan (diameter 1 m), speed of rotation variable
7 Electric motor (1460 rpm, 20 HP)
8 Regulation of fan speed
9 Sand tray
10 Saltiphone
11 Sediment catcher

Figure 4. Scheme of wind tunnel (adapted from Knottnerus, 1979) and of experimental set-ups A and B, described in the text

system (Spaan and Abeele, 1991; Lima *et al.*, 1992). Raindrops are not registered by the saltiphone (Spaan *et al.*, 1991; Lima *et al.*, 1992);

equipment for data registration (every 6 s) and storage (every 10 min).

Sometimes, under storm conditions, the membranes of the microphones installed at 0·1 and 0·2 m became clogged with wet sand particles which disturbed the measurements. Strong winds in drier conditions often unclogged the membrane; otherwise the obstructing sediment was removed manually.

THE WIND TUNNEL EXPERIMENTS

The wind tunnel used in the laboratory experiments has a cross-section of a 0·75 m × 0·75 m and the test section is 19·5 m long. The tunnel walls consist of removable glass windows. It is a closed circuit in which the air is led from the tunnel, over the ceiling and back into the tunnel (Figure 4). Wind flow is created by a fan and can be controlled with a set of blinds. The wind velocity was measured with a pitot tube in the centre of the tunnel, at 0·3 m above the surface.

Schiermonnikoog sand, taken from the beach (Table I), was placed in the tunnel in series of trays measuring 0·33 m × 1·22 m. These trays were weighed before and after the erosion experiment under oven-dry conditions to determine the amount of sand that was removed by wind action during the experiments.

The influence of soil moisture on the initiation of saltation was investigated by wetting the sand homogeneously and then gradually increasing the wind velocity in the tunnel (Figure 4, set-up A). The saltiphone, installed as close as possible to the sand surface (~35 mm), was used to determine the wind velocity at which saltation of particles started. The water content of the sand surface was measured with a reflection-photometer (Schäfer, 1989) before and after the experiment, which lasted about 2 min.

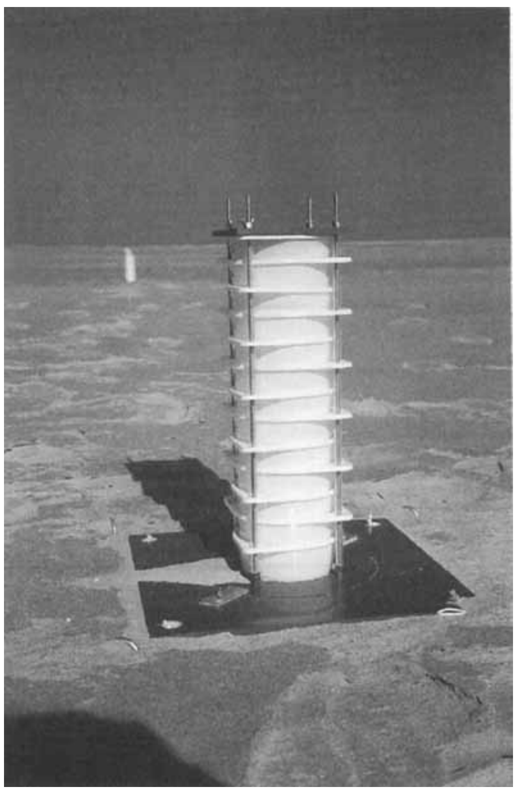


Figure 5. The vertical sediment trap used for the sediment profile measurements in the wind tunnel (Figure 4, set-up B). Height of the sand trap is 0·33 m

At the beach plain of Schiermonnikoog, an alternation of wet spots and spots of (blown) dry sand was frequently observed. Field measurements indicated that in such a situation the erosion threshold velocity is not significantly higher than in a situation with merely dry sand. In contrast to the dry spots, very few particles are lifted from the moist parts and creeping of sediment is not visible by eye. However, the saltation process continues over these moist surfaces. In order to study transport of saltating sediment over surfaces with different moisture contents, the following experimental set-up was utilized (Figure 4, set-up B). The effect of the soil surface moisture content (θ_s) on the mass distribution of saltating particles with height during transport was measured with a variant of the De Ploey vertical sand trap (Figure 4, set-up B) (De Ploey, 1980). It consists of 14 small containers mounted one above the other at a spacing of 22 mm (Figure 5). These traps were calibrated in the wind tunnel by van Dijk and Hollemans (1991). Six trays were installed windward of the sediment trap: four with homogeneously wetted sand and two with air-dried sand (Figure 4, set-up B). The trays were positioned so that the air stream first reaches the dry sand where transport starts. This dry material then moves along about 5 m of wetted sand, which changes the vertical sediment distribution before the particles are eventually captured in the containers of the sediment catcher. The length of 5 m is sufficient for this purpose because, normally, all saltating particles contact

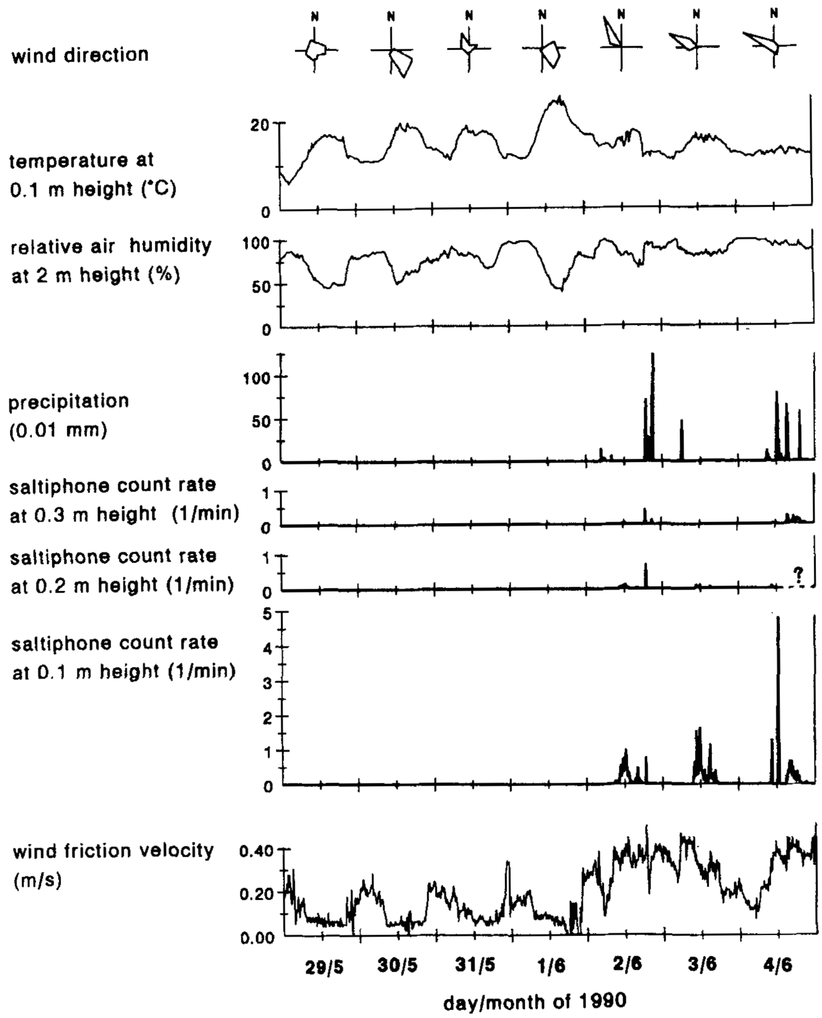


Figure 6. Time series of the wind direction, air temperature, relative air humidity, precipitation, saltiphone count rates and wind friction velocity for a selected period of 7 days (29 May to 4 June 1990)

the surface within about ten times the saltation height, which is below 0·2 m for most particles (Spaan *et al.*, 1991; Williams, 1964). Experiments were carried out for six different moisture contents and a constant wind velocity (9 m s^{-1} at 0·3 m above the sand surface). Each trial lasted about 5–7 min.

RESULTS

Field experiments on Schiermonnikoog Island

A period of 7 days was selected from the data-set in order to illustrate the measurements carried out on the beach. Figure 6 shows time series for the wind direction, air temperature, relative air humidity, precipitation, the number of particle impacts recorded by the three saltiphones, and the friction velocity. The wind friction velocity (u_*) was calculated with the following expression:

$$u_* = u(z)\frac{k}{\ln(z/z_0)} \qquad z \geqslant z_0 \tag{1}$$

where $u(z)$ is the wind velocity (m s^{-1}) at height z, z_0 is the roughness length (m), z is the height above z_0 (m) and k is Von Kármán's Constant (~0·4). Both z_0 and u_* were obtained from regression analysis, using the wind velocities measured at 1, 2 and 10 m height.

Figure 6 shows that sediment transport also takes place during rainfall. The sudden drop in recorded saltation fluxes once rain stops, as observed frequently in the 3 month period of the experiments (Lima *et al.*, 1992), can be attributed to increased soil resistance to wind erosion. The duration of this effect is variable and depends on many meteorological and soil factors.

Figure 7 shows the relation between the wind friction velocity and the number of particles counted with the saltiphone at 0·3 m above the surface for nine isolated wind/rain events. At equal friction velocities, observations with rain show, in general, higher saltiphone count rates than the observations without rain (Figure 7, points inside dashed circles). Figure 7 also shows that during rainfall, sediment can be moved under conditions where no motion is predicted by aeolian processes (points inside the left-hand circle). These effects can be attributed to the splash–saltation process.

Figure 8 shows the cumulated number of particles counted by the saltiphones for a period of 5 weeks

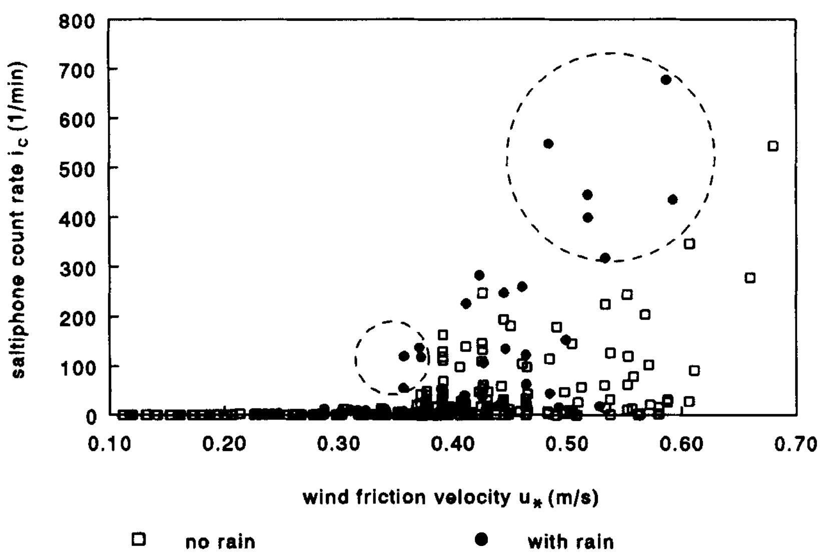


Figure 7. The effect of rainfall on splash–saltation: the relation between the saltiphone count rate (i_c) and the wind friction velocity (u_*) with and without rainfall (nine wind/rain events in the period 3 April to 25 June 1990)

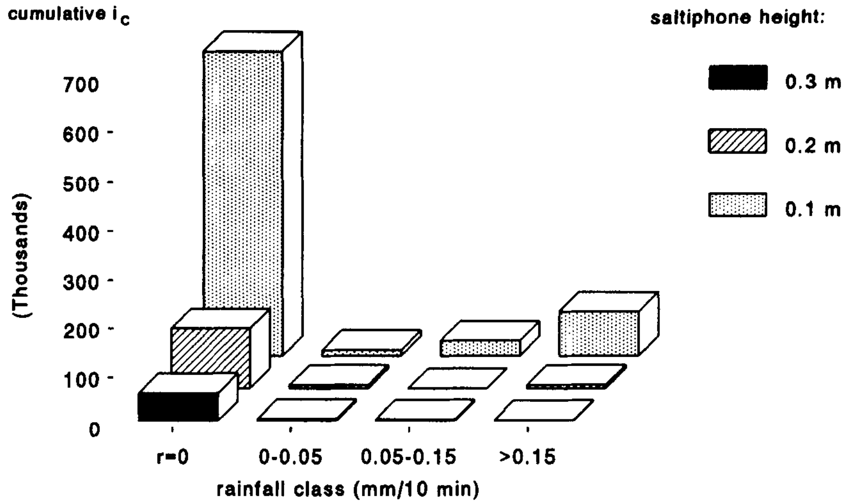


Figure 8. The total number of particles recorded by the three saltiphones (i_c) for four classes of rainfall intensities (7 May to 10 June 1990)

for four rainfall classes. Clearly, the bulk of sediment transport by wind takes place under dry weather conditions and the relative importance of splash–saltation transport is rather small. The contribution of splash–saltation to total sediment transport by wind is, however, significant, especially at higher rainfall intensities.

Wind tunnel experiment set-up A (see Figure 4)

Field experiments on the beach of Schiermonnikoog revealed a value of about 0·17 m s^{-1} for the threshold friction velocity u_{*t} under conditions of a completely dry sand surface (Spaan *et al.*, 1991). However, during most erosion events u_{*t} varied between 0·25 and 0·35 m s^{-1}, depending on the surface moisture content. The wind tunnel experiments show that the minimum wind velocity needed to start saltation of the Schiermonnikoog beach sand increases considerably with the surface moisture content (Figure 9). As the wind profile in the tunnel differs slightly from the logarithmic profile that is normally found in nature, it was not possible to

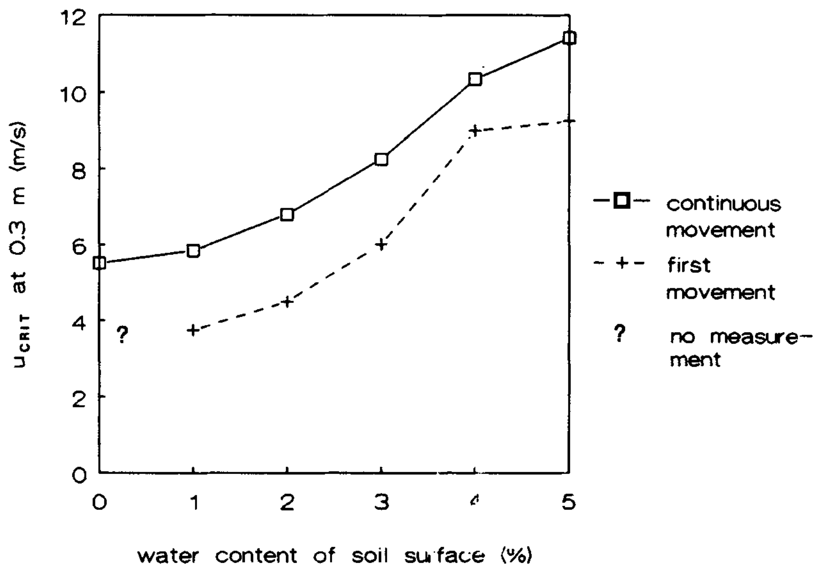


Figure 9. The influence of the gravimetric surface water content (θ_s) on the threshold wind velocity of motion in the wind tunnel (velocity measured at 0·3 m height (u_{crit}))

calculate the friction velocities of the experiments. However, the experiments in the wind tunnel show that surface moisture content is a very important factor, which largely determines the threshold velocity.

In Figure 9 a distinction has been made between 'first movement' and 'continuous movement': 'first movement' refers to movement of only a few individual particles followed by periods of no movement; in the case of 'continuous movement', moving particles are observed everywhere above the surface. Similar relations between θ_s and the threshold wind velocity were found by other researchers (e.g. Svasek and Terwindt, 1974; Sherman and Hotta, 1990; McKenna-Neuman and Nickling, 1989).

Wind tunnel experiment set-up B (see Figure 4)

In most cases, the vertical distribution of soil mass transported by saltation can be described by an empirical negative exponential equation (Horikawa and Shen, 1960; Williams, 1964):

$$q_z = q_0 e^{-\alpha z} \tag{2}$$

where q_z is soil mass transported at height z ($kg\,m^{-2}\,s^{-1}$), q_0 is the extrapolated saltating soil mass transported at the surface ($kg\,m^{-2}\,s^{-1}$) and α is the decay coefficient (m^{-1}), a measure of the vertical concentration gradient.

The total saltating mass can be obtained by the integration of Equation 2 (the shaded area of Figure 10):

$$Q_s = \int_0^\infty qz dz = \frac{q_0}{\alpha} \tag{3}$$

where Q_s is the total mass transported by saltation ($kg\,m^{-1}\,s^{-1}$). It was assumed that saltating particles start moving immediately above $z = 0$ (Horikawa and Shen, 1960). Creep transport height was not considered in the analysis.

The vertical sediment distribution during erosion is remarkably different when the sediment is being transported over a wet surface instead of a dry one (Figure 11).

The profile measurements with the vertical catcher show that the decay coefficient (α) decreases significantly with θ_s (Table II; Figure 12). Particles that move in saltation over a wetted surface will hardly be able to cause movement of surface particles as these are held by cohesive forces. On the contrary, particles hitting a dry surface will initiate movement of other particles and will thus lose part of their kinetic energy.

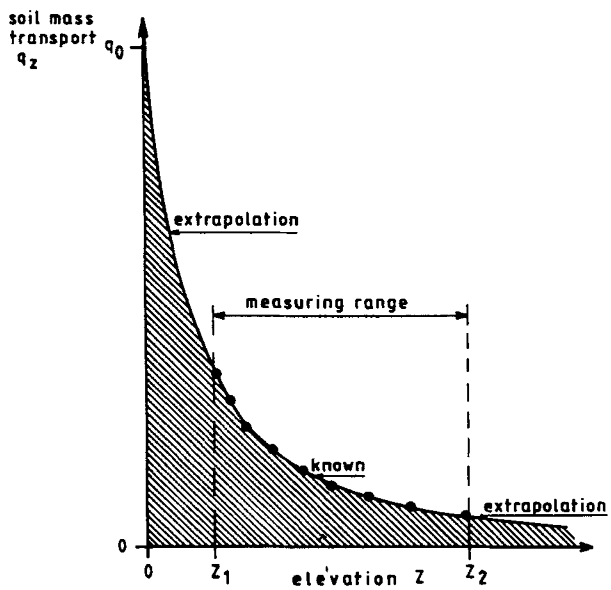


Figure 10. The distribution of transported sediment with height, with an indication of the measuring range (known) and the parts of the profile that have to be extrapolated to determine the total amount of sediment transported by saltation (shaded area)

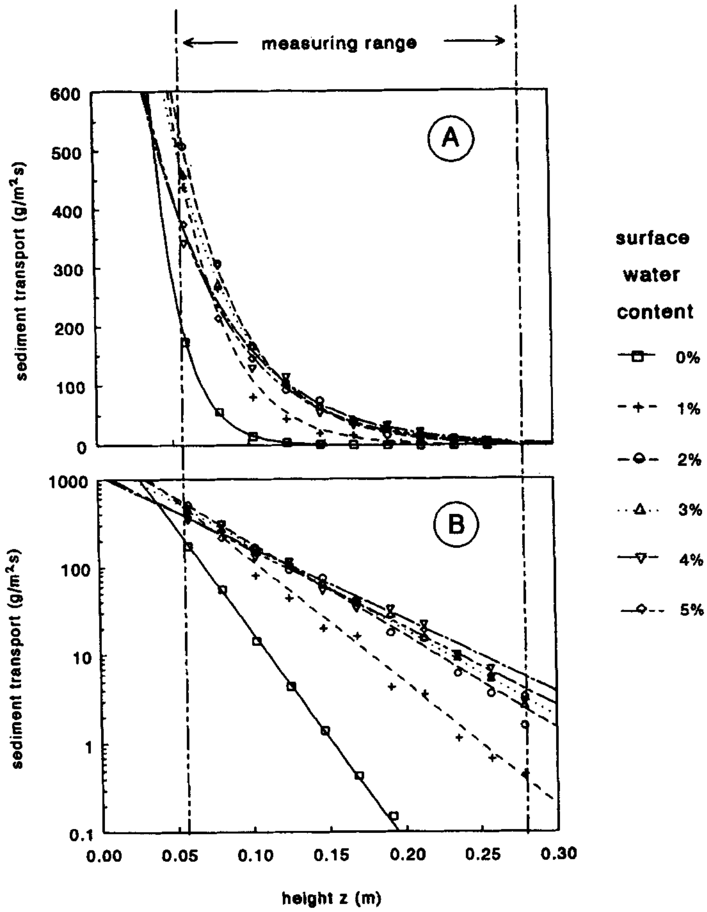


Figure 11. Vertical distributions of sediment transported over sand surfaces for different moisture contents (wind tunnel experiments with a constant wind velocity of 9 m s^{-1} at 0·3 m height). Sediment transport is shown on (a) linear and (b) logarithmic scale

Therefore, the collisions of particles on a wet surface will result in higher jumps of saltating particles, which will be reflected by a decreasing slope in the logarithmic sediment profile. Figures 11 and 12 also show that this effect is most important for θ_s up to 2 per cent.

The extrapolated sediment flux at the sand surface (q_0) decreases strongly with θ_s (Figure 12) because cohesive forces resulting from moisture limit the detachment of particles by wind drag. As a result, the

Table II. Parameters for the sediment profile equation (Equation 2 and Figures 11 and 12)

	Profile and regression parameters				
gravimetric θ_s (%)	q_0 (g m^{-2} s^{-1})	α (m^{-1})	n	r^2	Q_s (g m^{-1} s^{-1})
0	4607·9	55·1	7	0·998	83·5
1	2946·1	31·9	12	0·986	92·4
2	2117·8	24·2	13	0·998	87·6
3	1712·9	22·4	13	0·999	76·4
4	1113·4	18·9	13	0·962	59·0
5	1212·4	20·3	13	0·992	59·6

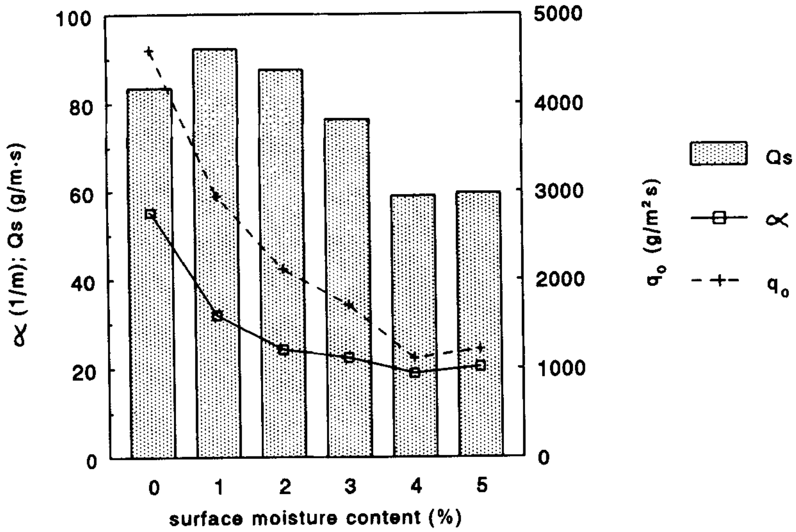


Figure 12. The influence of the surface water content (θ_s) on the decay coefficient (α), the extrapolated saltation transport at the sand surface (q_0) and the total saltation transport (Q_s)

transport energy of the wind flow near the surface will increase and particles that are lifted will, on average, describe higher trajectories. The total saltation transport rate (Equation 3), measured at the end of the wetted surface, in general decreases with increasing surface moisture (Table II and Figure 12). This result contradicts the results of Sarre (1988), whose experiments concerned sediment with similar texture. The results of experiment A (Figure 9) show that detachment by wind drag at the wind velocity used in experiment B becomes negligible at surface moisture contents of 4 per cent or more. This explains why total saltation transport (Q_s) at 4 and 5 per cent moisture content are equal (Figure 12): the wet surface merely functions as a transport plain for the material already in saltation.

Although the effects of surface moisture on vertical sediment transport profiles come out rather clearly in the experiments, they have not been mentioned by other researchers.

The moisture content of the soil surface appears to be an important factor in wind erosion of beach sands, affecting transport processes. This underlines the necessity of taking into account the moisture conditions of the soil surface in wind erosion research.

CONCLUSIONS

Most predictive wind erosion models assume no transport of sediment by wind during rain. Also, parameters related to cohesion due to moisture are rarely taken into account. This study shows that the effect of rain and consequent surface moistening on the transport of non-cohesive soil material by wind may be important. This is evident from field experiments with an acoustic sediment sampler and from wind tunnel experiments.

Wind tunnel experiments showed that an increasing moisture content of the surface sediments: (a) increased the threshold wind velocity of motion; (b) decreased the vertical concentration gradient of the transported sediment; (c) decreased the extrapolated saltation transport flux at the sand surface, assuming a negative exponential dependency of mass transport with height. These three effects are interrelated and are due to cohesive forces induced by rainfall moistening the sand.

Field measurements showed that *during* rainfall: (a) sediment transport occurred in situations where no motion would be expected regarding the friction velocity of the wind; and (b) the number of impacts of sand particles at the height of the sediment sensors in general increased. The first effect indicates detachment of sand particles by splash action. The second effect agrees with the findings of the wind tunnel experiments: a wet surface changes the character of particle impacts, leading to higher saltation trajectories.

Splash–saltation processes may contribute significantly to sediment transport in situations where no

motion is predicted by aeolian processes. Therefore predictive models which do not account for this interaction may underestimate sediment transport. This study shows that the estimation of sediment transport by wind during rainfall is difficult, because of the opposing factors (detachment by splash versus cohesion forces) that play a role in the process.

ACKNOWLEDGEMENTS

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